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CONSTRUCTION AND OPERATION OF LOW-PRESSURE DAMS ON PERMAFROST SOILS

G.F. Biyanov

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HANOVER, NEW HAMPSHIRE

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During the construction and operation of frozen dams, just as for the construction of dams by the thaw method, but for their operation as such, frozen soils may be used for the foundation. However, the foundation soils must not be allowed to thaw. Filtration through the body and foundation of a dam should be completely precluded. Otherwise losses of the filtration resistance and overall strength of the facility will occur. The requirement of ensuring against filtration through the body and foundation of a dam or in the bank

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[one word illegible] and its abutment with the spillway must also be observed during the construction of dams by the thaw method. Filtration eventually promotes the formation of a thaw zone, increased filtration and the overall stability of a dam on rocky soil is lost. During the construction of dams on ice-saturated sedimentary soils, the latter must be completely stripped from the foundation if their thickness is insufficient, and [possibly replaced] with high-quality soils. If the thickness of ice-saturated soils is substantial, then the core of the dam must be filled with less ice-saturated soils as a tooth. The latter should completely cut through the ice-saturated soils. The dimensions of the spillway should be determined on the basis of careful analysis of the hydrological mode of the stream. Wherever relief permits, the spillway should be built outside of the front created by the dam. Otherwise filtration may occur, altering the thermal mode of the facilities, resulting in inevitable losses of filtration resistance.

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Several low-pressure dams have been constructed of local material in the Vilyuy River basin for flood control, reservoirs, for flooding [one word illegible] ranges and for tailings disposal of mining enterprises.

The dams were erected in the lower course of the Irelyakh River and [possibly its] tributaries. The construction region is characterized by a decidedly continental climate. The absolute minimum air temperature is minus 83°C and the maximum is 35°C. The mean monthly temperature of the coldest month (January) is minus [illegible].6°C; the warmest (July) is plus 17.9°C. The mean annual temperature is minus 8.2°C.

The average long-term precipitation does not exceed 250 mm, fluctuating from 150 to 350 mm. The snow cover begins to form in early October and becomes continuous in the same month. There is negligible wind activity.

The Irelyakh River, in terms of the character of its water mode, is in the class of rivers with spring flooding, low summer level and summer-autumn high water. During the spring flooding period the water level rises 2.5-3.5 m. The maximum discharge rate of the river has a 1% recurrence rate and reaches 172 m^3/s. The maximum discharge during the construction period was 158 m^3/s. The discharge of the river in annual cross section is extremely irregular, and more than 90% of it occurs during the spring flooding period. During winter the discharge ceases; the river and its tributaries freeze over. Thaw persists under the river bed, through which sub-bed ground water flows. The heating effect of the underground flow is so great that the thickness of the sub-bed thaw reaches 8-10 m.

The Irelyakh River valley has an average width of 200-500 m, broadening to 1,800 m in the lower reaches; the bed cuts 4-5 m into the first flood plain terrace, within which it forms sharp bends. Bed width in the reach sections is 35-40 m.

The valley of the Irelyakh River and its tributaries are cut in rock strata of the Ust'-Kutskiy stage of the Ordovician lower Paleozoic, and only in the water divides are they covered in places by Jurassic continental

sediments. The slope and bedrock floor are made up of Ordovician sediments of the Lower Paleozoic, chiefly marlaceous clay and loam with seams and strata of dolomite, dolomitized limestone, sandstone and [one word illegible] marl with an ice content of 15-20%, and up to 45% in the upper horizons. The Ordovician sediments are deposited nearly horizontally at small [possibly dip] angles. However, during excavation of the trench for the spillway of dam No. 7 in the right wall of the valley, and during excavation of the spillway channel of dam No. 9 in the left wall, folded formations were exposed with a dip angle of up to 60°.

The entire mass of Ordovician sediments, to a depth of 30-40 m from the earth's surface, is subjected to intensive weathering, in which freeze weathering processes, characteristic of permafrost regions (the formation of freeze cracks, [one word illegible] displacements, freezeout processes, etc.), play an important role in addition to ordinary physical and chemical weathering processes.

Quaternary sediments are extensively developed in the form of slide rock sediments, and also alluvial bed sediments in the Irelyakh River valley. The slide rock sediments, with a solid 1.5-5 m thick mantle, overlie the [possibly slopes] and water divides. On the surface are brown clays, containing up to 40-50% rubble and flaky fragments of Ordovician carbonate rocks, below which the color changes to gray and greenish gray.

The bed alluvium, 1.5-2 m thick, occupies the [possibly lower] belt along the river itself and consists of fine-grain sand and loam with a small amount of Jurassic gravel sediments. In some parts of the bed there is no alluvium, and none at all in its tributaries.

Deposited among the sediments of the first flood plain terrace are, on the surface, silty loam, silt with a substantial amount of vegetation fossils, often with thin seams of loam and fine-grain sand. In some sections there are peat and, buried beneath it, mineral ice formations.

The thickness of the active stratum is comparatively small and, depending on the exposure of the slopes, reaches the maximum value (1.5-2 m) on slopes with a [one word illegible] exposure, and not more than 0.5-1 m on slopes with a northern exposure.

The surface of the water divides is covered by a dense forest of scrubby [possibly deciduous] trees, unsuitable for construction purposes.

The first flood plain terrace is situated basically along the left bank and is quite well expressed morphologically, having a width of up to 150-300 m, is substantially marshy and is covered with sparse, short underbrush.

The construction region is situated in a zone of continuous permafrost, the thickness of which was determined by temperature observations in deep

Table 1

Дата измерения (1)	Глубина, м (2)									
	1	2	4	6	8	10	20	60	120	170
9.УШ-57	+1,1	-1,7	4,6	5,2	4,9	4,0	2,9	2,8	2,7	2,6
12,X-57	-0,1	-1,3	3,3	4,2	4,4	4,3	–	3,1	2,9	2,6
9.XП-57	-3	-1,4	2,6	3,4	4	4	3,2	3,1	2,9	2,6
22.1-58	-7,8	-4,1	2,8	3,1	3,5	3,6	3,1	3,1	2,9	2,6
10.П-58	-9,8	-5,1	3,2	3,3	3,6	3,7	3,2	3,1	3	2,6
22.Ш-58	-9	-6,8	4,2	3,8	3,8	3,6	–	3	3	2,6
28.У-58	-0,1	-4,5	4,6	4,5	4,1	3,5	3,4	3	3	2,6
(3) Среднее	-4,1	-3,5	3,6	3,9	4	3,7	3,2	3	2,9	2,6

KEY: 1, Date of measurement; 2, Depth, m; 3, Average

exploratory wells and exceeds 250 m. The soil temperature from August through May, according to data of the "Tsvetmetproyekt" Institute, is presented in Table 1 as a function of depth.

The ice saturation of the seasonal thaw layer and permafrost stratum is highly irregular. The ice content of marlaceous clay is represented by seams and lenses of ice, varying in thickness from fractions of a millimeter to 1-2 cm, and in rocks it is present in the form of thin (1-5 mm) ice seams and ice films, enveloping plate coal and fragmented material.

The alluvial sediments of the flood plain terraces are characterized by the highest ice concentration. Encountered in silty clay and loam are ice lenses up to 1.5 m thick with considerable extent.

The physicomechanical properties of the rocks of the Irelyakh River valley are characterized by the data in Table 2.

Table 2

Показатели 1	Делювиальные суглинки 2	Илы аллювиальных отложений 3	Мергелистые глины 4
5 Естественная весовая влажность	8,8–88,8	12,3–152	14,3–54
6 Объемный вес	1,48–2,3	1,21–2,2	1,57–2,15
7 Пористость	22–67	27–82	28,5–62
8 Коэффициент пористости	0,24–1,81	0,32–4,10	0,38–1,83
9 Относительное сжатие, см/м			
10 при $P = 0$ кг/см^2	0,4–4	14,9–43,4	0,4–1,2
при $P = 1$ кг/см^2	0,45–9,5	18,75–48,78	1,1–4,2
при $P = 2$ кг/см^2	0,5–11	19,45–48	4,8–7,3
при $P = 3$ кг/см^2	3–11,85	–	5,2–9,75

KEY: 1, Properties; 2, Slide loamy clay; 3, Silts of alluvial sediments; 4, Marlaceous clay; 5, Natural moisture content by weight; 6, Density; 7, Porosity; 8, Porosity factor; 9, Relative compression, cm/m; 10, for P = , kg/cm^2

Because of the high ice saturation of the silty soils of the first flood plain terrace their relative compression during free thawing changes from 4.9 to 43.4 cm/m, and from 16.75 to 48.75 cm/m under a load of 1 kg/cm^2.

The hydrogeological mode of the basin is characterized by three aquifer horizons: subpermafrost, intrapermafrost and suprapermafrost. Only the subpermafrost horizon, the reservoir rocks of which are thawed soils, deposited below the permafrost stratum, is permanent. The other aquifer horizons are subjected to permafrost and seasonal changes. The subpermafrost pressure horizon, with a level 70 m below the valley floor level, has no effect on the operation of the installations and construction conditions.

The suprapermafrost, pressureless aquifer horizon is situated in the seasonal thaw stratum; its reservoir rocks, too, are basically slide loamy clay sediments. This aquifer horizon is analogous to vadose water and depends on the amount of precipitation, the ambient air temperature, reservoir rocks and the character of relief; it usually freezes in the winter.

The intrapermafrost ground waters are situated in thaw formations and occupy an intermediate position. This group includes the sub-bed ground water stream, confined within the sub-bed thaw.

During early summer and heavy rain periods the level of the suprapermafrost waters in level and gently sloping sections reaches the earth's surface and even exceeds it, forming a temporary marsh. The discharge of suprapermafrost waters from slide sediments was determined by samples, taken in June, to be 0.03 to 0.10 liter/s.

During winter the seasonal thaw layer freezes over much of the territory, all the way down to the roof of the permafrost rocks.

To answer the question of the feasibility of using subpermafrost waters for industrial and drinking purposes, hydrogeological test wells were drilled. A well, drilled to a depth of 358 m, tapped an aquifer horizon at a depth of 320 m. Among the reservoir rocks are Cambrian carbonates with fissures, partially filled with gypsum and bitumen. The piezometric water level is 70 m below the well head. The influx of water into the well, determined by test pumpings with a sludge pump, was 0.2-0.3 liter/s, and 0.8 liter/s in another well, in which the piezometric level was 25 m. The stable, high salinity and low yield of the wells make the subpermafrost waters of the region completely unfit for industrial and drinking purposes.

Thus the only source of industrial-drinking water can only be the surface runoff of streams, which is extremely irregular in annual cross section. This is why it is necessary to build reservoirs.

Dam No. 1 backs up a reservoir for industrial-potable water supply. The dam was constructed with intact permafrost in the base and with a frozen curtain.

It is important to note that Soviet Arctic hydroengineering construction practice as yet has no experience in the construction of such facilities.

The reason for this is that many planning decisions regarding the construction of installations and recommendations on the completion of work contained serious deficiencies.

A hydraulic engineering complex consists of an earth-fill dam, spillway and ice shield wall in the form of [one word illegible] buttresses, through which passes a road bridge. The earth-fill dam (Figure 1), with a maximum height of [illegible] m and a length of 320 m, backs up a reservoir with a capacity of [illegible] cubic meters.

The central part of the dam is filled with loamy clay and the side load-bearing prisms with fine-grain [possibly sand]. The slopes of the dam are reinforced with fill rock. A heat-insulating moss cover, 100 cm thick, also covering the top of the slopes, was planted on the crest of the dam.

The dam was built by the thaw method with subsequent freezing. An air freezing system for artificial freezing of the central part of the dam was installed to promote the freezing of the dam and to prevent possible filtration. The frozen core of the dam should close with the permafrost in the foundation. The freezing system includes a system of vertical pipes, through which outside air, with a temperature below -15°C, is pumped under pressure.

The spillway is situated outside the body of the earth-fill dam on the left bank slope of the river and is an open, self-regulating trapezoidal channel with a floor width of 40 m and has a stepped fall. The slopes and floor are reinforced by prefabricated reinforced concrete slabs. The canal is designed to pass a calculated discharge of 0.1% recurrence at a rate of up to 358 m^3/s.

For the purpose of dissipating the energy of the stream, the stepped fall has four steps, each with a height of 2.20 m. The fall steps are reinforced concrete slabs, placed on a reinforced concrete pile grate, buried under 5 m of frozen soil.

The foundation of the dam rests on bedrock and Quaternary sediments. The latter are made up basically of bed sediments, alluvial sediments of the first flood plain terrace on both banks, eluvial loamy clay and slide sediments on the valley slopes.

Alluvial bed sediments are made up of silt with rubble and gravel, silty loam, gravel-rubble sediments with a sand filler. The soil is permafrost and, within the sub-bed thaw, it is thawed.

The alluvial sediments of the first flood plain terrace are made up of silty loam and silt with a high concentration of plant fossils, and have a high ice content -- up to 60%. The concentration of various ice [one word illegible] in silts reaches 90%. The ice in these sediments is [possibly distributed] uniformly in the form of lenses and seams up to 0.5 m thick. In some sections there are peat deposits, under which have been found buried

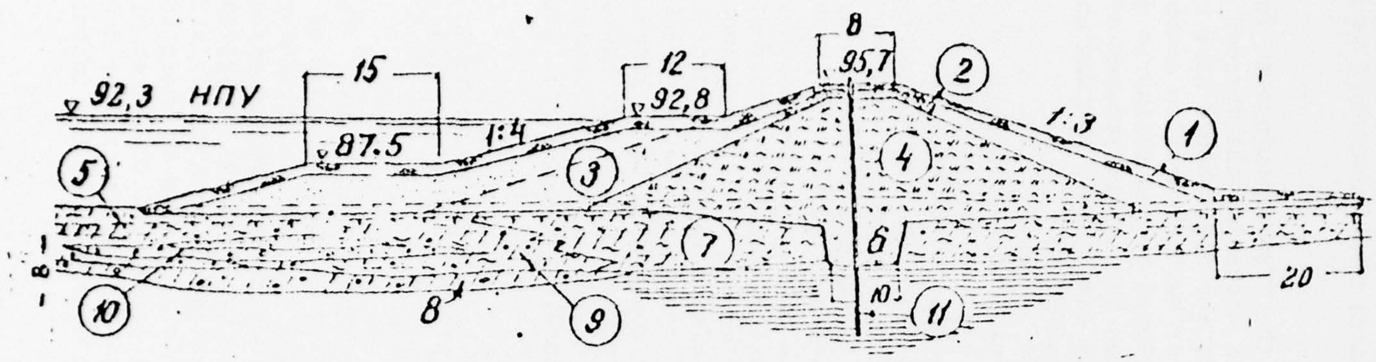

Figure 1. Dam No. 1: 1 -- rock rubble reinforcement of slope; 2 -- moss-peat heat-insulating layer; 3 -- sand fill; 4 -- loamy clay core; 5 -- boundary of permafrost; 6 -- *loamy clay tooth of dam*; 7 -- swollen silted loamy clay, up to 60% ice content; 8 -- loamy clay with marl rubble; 9 -- silty loam with gravel, rubble; 10 -- sand with plant fossils; 11 -- frozen curtain wells.
[НПУ=Normal backwater level]

ice lenses. The high ice concentration of these sediments obviously causes considerable subsidence during thawing and makes them unsuitable as materials for the base of a dam.

According to the blueprint, drafted by the "Tsvetmetproyekt" Institute, these loose, ice-swollen Quaternary sediments, covering the bedrock in a layer up to 3 m thick under the foundation of the dam, should have been replaced by high-quality soils. The volume of such excavation amounted to more than 130,000 cm^3. The blueprints, developed by the Leningrad department of the "Gidroproyekt" Institute, retained the entire stratum of Quaternary sediments in the foundation of the dam. Thus, the dam was [possibly planned] on unreliable ice-saturated soils.

Changes were later made in the construction of the facility at the suggestion of the builders. In particular, a tooth, which completely cut through the ice-saturated Quaternary, less reliable (in terms of bearing capacity), ice-saturated soils, and extended 0.5 m into the bedrock, was constructed for the purpose of fastening the body of the dam to the foundation. The width of the tooth was [one word illegible] at 12 m in accordance with construction conditions, but it was later reduced to 8 m. Such mating of the core of the dam and the bedrock, which has a low ice content, and which retains its bearing capacity after thawing, guaranteed perfect antifiltration stability and the reliability of the dam. In this connection the builders suggested constructing the dam without a frozen curtain, since during construction of the tooth, which cut through the entire thickness of the Quaternary sediments, such a measure was considered to be largely superfluous, substantially increasing construction cost and overhead. However, the suggestion of the builders was rejected. It is important to note here that the plan of the spillway was completely revised at the suggestion of the builders.

The dam was placed in operation in 1964 and continues to be in satisfactory condition. The frozen curtain in the body of the dam makes perfect contact with the frozen foundation.

Dam No. 2 was built in 1957-1960 by the "Yakutalmaz" trust. The dam was reconstructed by VilyuyGESstroy in time for the spring flood of 1960. The plan of the installation had serious flaws, in many cases incorrect engineering decisions, and during the construction process significant [one word illegible] occurred. Serious violations of technical conditions were permitted to occur during construction operations. Consequently strong filtration occurred in the dam during the initial period of operation, and the spillway was completely destroyed during passage of the first high water. It is necessary in this connection to discuss in greater detail the experience in the planning, construction and operation of the installations of this facility.

The facility (Figure 2) includes an earth-fill dam, spillway and ice-confining installation. The length of the dam is 300 m, its height in the

bed section is 12 m and its width at the crest is 10 m. The horizontal equivalents of the upper and lower slopes are [possibly 1]:3 and 1:2.5, respectively. In the body of the dam is a cribwork diaphragm, the cells of which are filled with a crib of sand and ligneous loamy clay. The upper slope is reinforced with fill rock. At the base of the lower slope of the dam is an enclosed drain, which runs into a stone [possibly banquette] in the bed section. The plan called for the body of the dam to be filled with slide sand soil. It turned out during the process of construction that these soils acquire a fluid consistency when they become wet. Therefore the basic volume of the body of the dam was filled with local ligneous rubble marlaceous loamy clay.

During the course of construction the plan of the dam was altered in order to increase the capacity of the reservoir; its height was increased by 2 m. The dam was widened by filling the slopes with argillaceous loamy clay with up to 35% rock rubble.

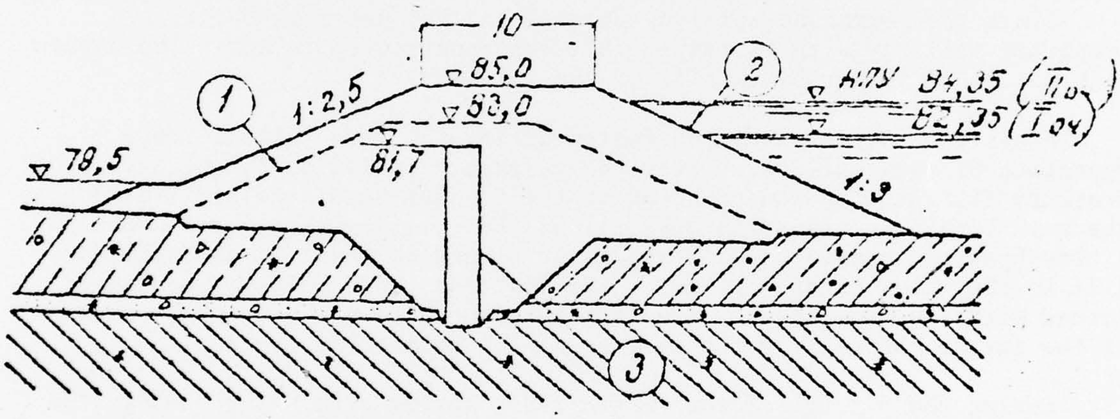

Figure 2. Dam No. 2: 1 -- contour of initial dam; 2 -- contour of dam after reconstruction; 3 -- cribwork diaphragm.

The spillway was initially planned as self-regulating with the threshold at the level of the sub-[illegible] horizon of the reservoir and was a [one word illegible] sill, the water discharge opening of which was [number illegible] m wide and 7.5 m long with a 100 m long spillway channel with a frame construction built on a pile foundation, lined with two layers of [one word illegible]. The span of the spillway is divided into three sections by [one word illegible] partitions.

The spillway was rebuilt in connection with the decision to increase the capacity of the reservoir. The plan called for the installation of a reinforced concrete slab at the threshold of the spillway, and a [possibly lifting] system in the form of rotating beams, [one word illegible] and gates, making it possible to raise the NPG [Normal backwater level] by 2.15 m

in comparison with the initial value. An ice retainer was built in the reservoir in front of the spillway in the form of groups of seven pilings, each 30 cm in diameter. A siphon spillway was provided in order to maintain the minimum sanitary water level in the [one word illegible] reach.

By the time of the spring high water of the first year of construction the left bank flood plain part of the dam had only been filled for a short distance, the cribwork diaphragm with soil filled cells collapsed and the intake and discharge channels were washed out. A [possibly pillar] remained in the entrance section of the intake channel, which served as a [possibly breakwater] for the channel trench and spillway, on which work was being done. The spring flood of the first year of construction passed through the natural bed, the banks of which were reinforced with facine mats in the section line of the dam. The river bed was sealed during the summer low-water period (August 1958) and soil was transferred from a previously prepared [one word illegible] by four bulldozers.

Since the permanent spillway channel had not yet been built, a temporary spillway with a stepped fall was constructed to admit the autumn high waters to the cribwork sill of the spillway.

Flaws of the plan were manifested during the very initial stage of operation of the facility. After the reservoir filled to the planned level pressure filtration began to occur in the foundation of the spillway due to the weak bonding of the cribwork sill of the spillway with the foundation. A clay upstream puddle blanket was later placed in front of the spillway sill in the water intake channel. The upstream puddle blanket was reinforced with concrete slabs. A cofferdam was built in the entrance section of the intake channel for the purpose of completing this work.

During the passage of the first (1959) spring high water through the spillway, the latter was virtually completely destroyed. During passage of the spring flood with 1% recurrence an ice jam formed around the piling clusters of the ice-confining [one word illegible]. Some of the pilings were severed and large ice floes crashed into the spillway. The timber partitions in the spillway channel first held the ice, but then they were ripped out and carried away along with the channel. During that time the left side of the channel was also destroyed; the end of the dam began to undergo rapid erosion on the spillway side.

Meanwhile the upper reach level continued to [possibly rise]; water began to spill over the crest of the dam. In this connection the right bank abutment of the spillway was [one word illegible] to save the dam. After that the upper reach level fell 21 cm in 3 hours and 1.44 m in 2 days. The upper reach level exceeded the calculated catastrophic level by 53 cm during passage of the flood.

During reconstruction the spillway was completely [one word illegible] with a cribwork construction, the cells of which were filled with clay. Its length was shortened to 32 m.

After reconstruction, completed by VilyuyGESstroy in 1960, the entire facility operated satisfactorily for 4 years; filtration through the dam was negligible.

In November 1964 the reservoir emptied and water remained only behind the cofferdam, erected during the construction period in the entrance section of the water intake channel and never dismantled. This circumstance predetermined the location and cause of leakage. The presence of a cavity in the foundation of the dam was established in the left abutment of the spillway. A cofferdam piling was constructed in front of the spillway to arrest the filtration stream.

During the initial period of operation of the facility observations were conducted on the temperature and filtration modes of the dam and its foundation. The temperature mode of the floor of the reservoir was studied. Unfortunately, the KIA [Measuring apparatus] system eventually failed. In this connection the temperature and filtration modes of the dam were known only for the first 2-2.5 years of operation.

Observation of the temperature mode of the body and foundation of the dam was conducted with [possibly resistance] thermometers, installed in special wells. The wells were lined with 50 mm diameter gas pipes, the bottoms of which were capped.

Observation of filtration in the body of the dam was conducted in three piezometric sections.

During the first year of operation the zero isotherm in the foundation of the dam fell by 1.2 m, and by 1.4 m more during the second year, under the influence of the filtration stream. Thus the upper boundary of the [one word illegible] fell by 2.8 m in 2 years as a result of the filtration stream.

Figures 3 and 4 show the isotherms through the longitudinal cross section of the dam for 1 June 1960 and 1 [possibly June] 1961. The figures show that the left bank flood plain part of the dam completely froze and the core of the thaw zone shrank in the area of the bed section. The zero isotherm under the spillway dropped to 12 m due to considerable filtration through the fissured bedrock. This degradation of the permafrost under the spillway does not pose a danger to the dam itself, since the spillway was built on soils, the bearing capacity of which is not affected by a change of the thermal [one word illegible]. However, increased filtration may result in [possibly heating] of the foundation in the spillway abutment and lead to increased filtration [one word illegible] of water. This assumption was eventually confirmed. Filtration decreased as the water level of the reservoir fell. When the water levels in the reservoir fell to the crest level of the temporary cofferdam in the intake channel filtration of water into the lower reach ceased. This showed that the source of the filtration stream was located in the intake channel between the temporary cofferdam and the spillway.

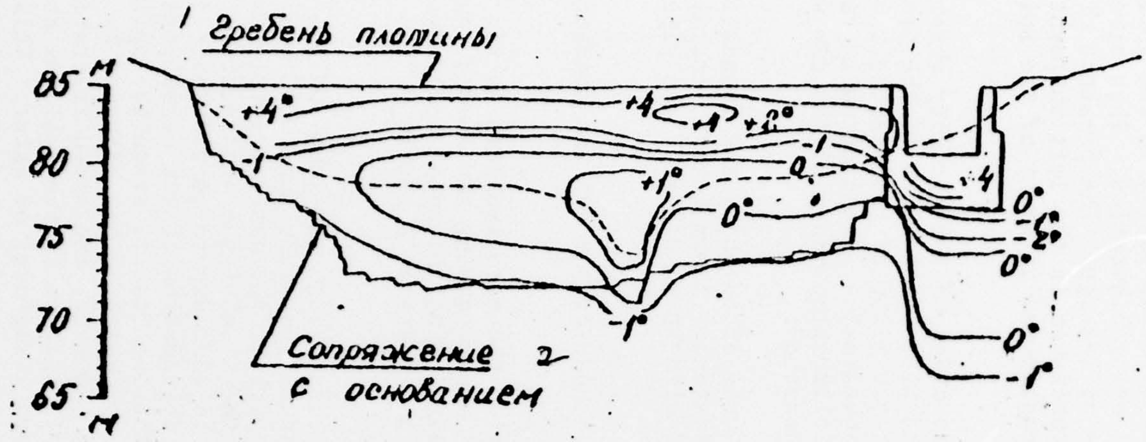

Figure 3. Isotherms in body of dam on 1 June 1960.
KEY: 1, Crest of dam; 2, Foundation abutment.

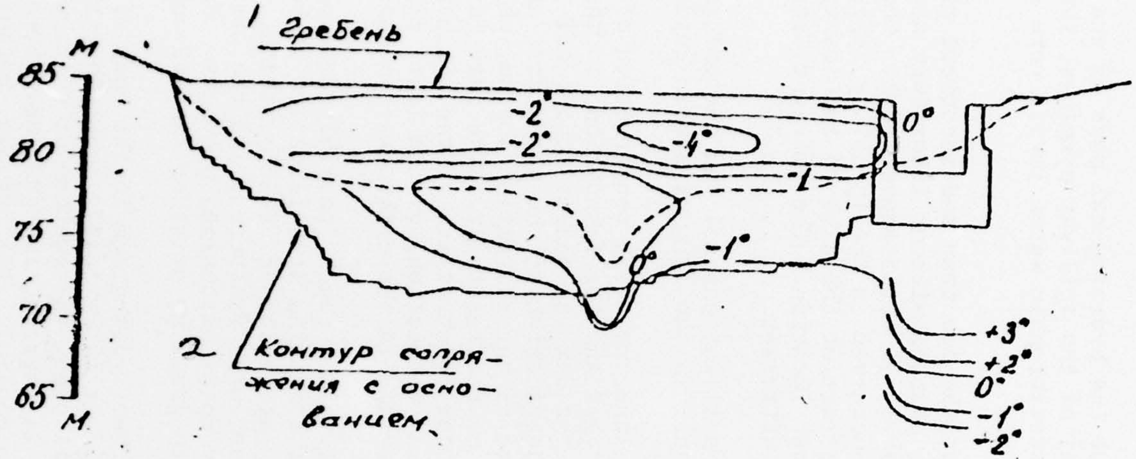

Figure 4. Isotherms in body of dam on 1 June 1961.
KEY: 1, Crest; 2, Contour of foundation abutment.

The basic factors that cause the destruction of the spillway during the first year of operation of the facility and dangerous leakage of water in 1964, are the following:

1. Not enough was known about the hydrological mode of the river, so that the [possibly cross sections] of the spillway openings, the [possibly crest] level of the dam and the catastrophic water levels were not determined correctly.

2. Unreliable construction of the ice trap and incorrect placement of this installation. The ice trap, planned without laboratory studies, was placed in the zone of the fall curve, in its steepest part. Consequently intolerably high flow velocities occurred in the [possibly approach] to this installation. During reconstruction the axis of the ice trap was moved 10 m upstream from the former location. The piling clusters were [possibly replaced] by concrete buttresses.

3. Weak construction of the spillway channel and the presence of excessive resistances in the channel in the form of stream guide partitions.

4. Technically incorrect engineering, weak construction of the abutment of the cribwork sill of the reservoir and the foundation, so that the underground antifiltration contour of the dam was unable to cut off the filtration head. Therefore intensive degradation of the permafrost under the spillway began under the influence of the filtration stream, which formed during the first days of filling of the reservoir. The rate of degradation eventually increased due to the poor construction of the abutment between the dam and the spillway, [possibly compaction] of the loamy clay, both in the cribwork cells of the spillway and in the cribwork-foundation abutments.

5. Excavation of the spillway sill trench [possibly and] of the intake channel disclosed the presence of fractured stratification of bedrock in the right bank. Steeply dipping (at angles of 50-60°) strata, striking in the direction of flow of the river, were fractured, and the cracks did not always fill with ice or [possibly rock] weathering products. No measures were taken to seal the cracks with grouting or other kind of curtain.

6. The construction of a cribwork diaphragm in the body of an earth-fill dam cannot be considered correct. It is virtually impossible to mechanize the filling and compaction of soil along the contour of a cribwork and in its cells, and manual compaction is unproductive and, more importantly, its quality does not readily yield to control. Furthermore, because of varying degrees of settling of a relatively rigid cribwork construction with [possibly vertical] walls and of the earth-fill body of a dam at the interface of the soil and cribwork, cracks inevitably form.

Dam No. 3. The foundation of the dam is made up of Quaternary sediments 4.10-7 m thick, consisting of silty loamy clay and loam on top and gravely sediments on the bottom. The roofrock consists of marlaceous clay and marl, with interseams of limestone.

The 3.5 m thick layer of bed alluvium consists of sand and gravel sediments. The thickness of the sub-bed thaw zone is 7.5 m.

The earth-fill dam with a frozen core is [number illegible] m long, has a maximum height of 4.1 m and creates a 1.5 m pressure head (Figure 5). The frozen core of the dam, which acts as an antifiltration curtain, was built by layer-by-layer packing of frozen soil, flooded with water and allowed to freeze. The volumetric ratio of ice to soil was 1:1 and the density of the ice-soil [possibly curtain] is 1.2-1.5 t/m^3 [2]. The top of the frozen core of the dam, [possibly built] during the winter (February-March), is covered with a buffer heat-insulating layer of earth to a depth exceeding the depth of seasonal thawing of the soil in the vicinity of the construction site.

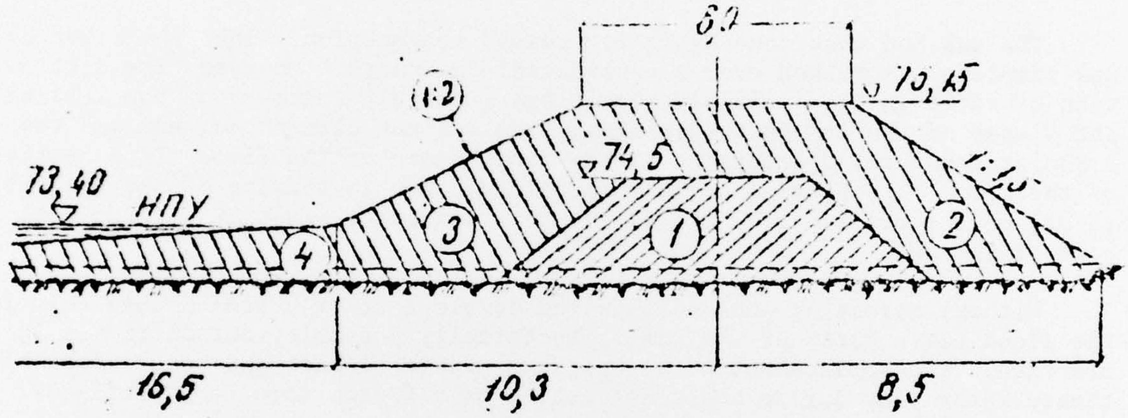

Figure 5. Dam No. 3: 1 -- frozen core; 2 -- lower wedge of dam filled with frozen soils; 3 -- frozen soil fill; 4 -- shield and upstream puddle blanket of thawed soils.

The crest of the dam is 2.75 m above the NPU [Normal backwater level] mark of the reservoir, and the level of the top of the frozen core is 0.15 m [possibly above] the maximum pressure level of the reservoir.

On the lower slope of the dam the heat-insulating layer is made up of frozen soil, and on the upper slope it is made up of thawed loamy clay, rolled flat in the spring. The fill of the upper slope was laid in the form of an upstream puddle blanket.

The sill of the spillway, located in the river bed, was designed as a cribwork. The silted icy loamy clays in the river bed under the spillway were supposed to be completely [one word illegible]. The sub-bed thaw zone in the sand-gravel [one word illegible] was to be crossed by a tooth in the form of a [possibly piling] wall, placed in a pre-excavated trench, packed with clay to seal holes.

A cribwork spillway of such design was not completed in time for the spring flood. In this connection the spring flood was allowed to flow through the natural bed. A cofferdam was constructed in the [one word illegible] of the spillway; the river bed below the cofferdam was scrubbed to a distance of 700 m through the entire cross section, with gangue rocks from an enriching plant, with a high concentration of silt and dust particles. Then the scrubbed bed was reinforced with fill rock; the ends of the flood plain sections of the dam on the spillway side were reinforced with fill rock. Thus a spillway channel was formed, the threshold level of which corresponds to the NPU mark. The width of the channel is [illegible]. The specific discharge during the passage of spring flood waters with a calculated [one word illegible] recurrence (160 m^3/s) is 3.2 m^3/linear m. This spillway has passed four spring floods and velocities have exceeded 2.5 m/s. No erosion has been observed in the spillway.

The sub-bed thaw zone basically ceased to function, since the river bed was completely scrubbed over a considerable distance. However, the filtration of water in the [possibly receiving] [possibly contour] of the threshold and slopes of the dam on the spillway side was not eliminated, nor was the associated natural degradation of the frozen core of the flood plain sections of the dam. This process began to accelerate due to thawing of the [possibly floor] of the reservoir, and a frozen core ceased to exist as a structural part of the dam.

Without arresting sub-bed thaw the development of a frozen core only in the flood plain parts of the dam is technically possible, but difficult in practice. The emplacement of an upstream puddle blanket and upper slope of thawed loamy clay during the construction of a frozen core is superfluous.

Dam No. 4 was constructed in the mouth section of the river and is a water-raising dam for flooding a placer area.

The engineering-geological conditions of the foundation of the dam are the following: Quaternary sediments up to 5 m thick on top, consisting of loamy clay, including up to 30-35% [one word illegible], and below of alluvial fine-grain silty [one word illegible] with inclusions of plant fossils. The bedrock is made up of marl with thin seams of limestone. The dam is a wooden structure with a cribwork sill and abutments built directly on the foundation. The width of the spillway is 20 m. On the sill is installed a water-raising system of the flood gate type with support frames, creating a head of 2 m. The rotating frames, during the passage of ice and spring flood water, are folded into the sill.

The cells of the cribwork are filled with loamy clay up to the floor level of the water apron, and above that with a sand-gravel mixture. The sill floor in the water apron section is concrete, above which it is covered with planks. There is a recess in the concrete floor of the water apron for accommodating the folded rotating beams of the water-raising system.

The cribs are framed with logs and are packed with [one word illegible]. The grooves are also sealed with planks for reliable water tightness and prevention of filtration through the abutments during filling of the cells with sand-gravel mass.

The dam was built during winter. Because of a shortage of clay, and also in connection with the fact that the laying of clay during that period involved substantial difficulties, the [one word illegible] tooth and floor of the water apron were made of cold [one word illegible].

The dam was built in the river bed. During construction a cofferdam was built across the river above the dam and the river stream was diverted through a specially constructed trench, dug in the flood plain. The pioneer trench was excavated with a bulldozer. It was later filled in with loam-gravel soil, and the upper slope is filled with a curtain of marlaceous clay of useful [one word illegible], transported for a distance of up to 25 km.

Dam No. 5 (Figure 6) was built to construct a tailings dump for an enrichment plant, but for the first 2 years it functioned only as a reservoir, which filled with spring flood waters and rainfall. The excess runoff was discharged through a side self-regulating spillway, built on the right bank with a threshold level 2 m below the crest level of the dam.

The length of the dam is 332 m and its maximum height in consideration of the [one word illegible] is 17.8 m. Its width at the crest is 5.5 m and at the bottom [illegible]. The horizontal equivalents of the slopes are: upper 1:3, lower 1:2.5. The [one word illegible] of the lower slope is the drainage prism.

On the sides, directly under the topsoil [one word illegible], to a depth of 1.2-1.5 m, are deposited slide loamy clays with up to 20-25% carbonate rubble, underlain by Ordovician carbonate rocks, weathered to the state of rubble-[one word illegible] material, alternating with frequency seams of clay, marl and [one word illegible], argillaceous limestone.

In the bed are deposited to a depth of 3 m strongly [one word illegible] silted loamy clays and silt, which acquire a flowing consistency after thawing. Farther down through the cross section the [one word illegible] soils are replaced by sand-gravel sediments with argillaceous filler, which again are underlain by [one word illegible] soils. The total thickness of the alluvial sediments, underlain by bedrock, is 4.5 m.

The topsoil layer was removed from the entire construction site during preparation of the foundation of the dam. Heavily iced [one or two words illegible] soils and rubble deposits [one word illegible] section under the tooth of the dam were removed and it was cut [one or two words illegible] marlaceous soils. The maximum depth of the [one word illegible] is 5.5 m. The topsoil was removed by bulldozers [two words illegible], and the trench for the tooth in silty soils [two words illegible] during the winter.

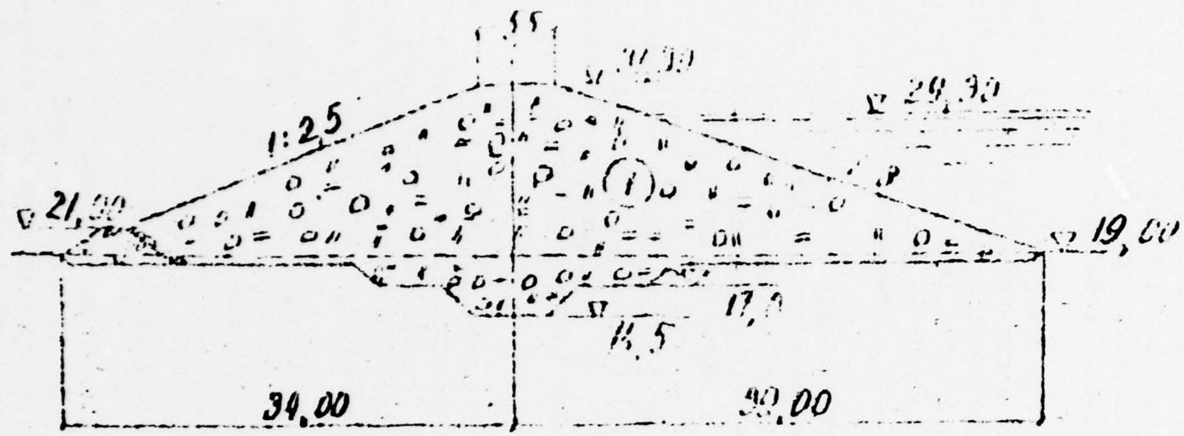

Figure 6. Dam No. 5: 1 -- [three words illegible].

The body of the dam, with a total volume of 95,500 m^3, was filled with slide loamy clays containing up to 20-40% [one word illegible] and plate-shaped rubble carbonate rocks of different sizes, deposited in a quarry with a thickness of [possibly 3.5 m].

The loamy clay was prepared in the quarry by bulldozers; as the upper layer thawed it was cut away and heaped into piles. The clay was transferred from the piles with excavators and transported by trucks to the fill site. After being leveled off by bulldozers the clay was rolled flat by [one word illegible] trucks.

During operation of the dam a head-[one word illegible] of water was observed under the foundation of the dam. The reservoir filled with spring flood waters in 1965. [One or two words illegible] on the left bank, 10 m below the dam, formed a [one word illegible] with an up to 0.5 m head and a discharge of up to [illegible], without erosion. Later on the discharge increased to [illegible] second. The source of the stream is located in the slope of the dam at a height of [one or two words illegible] of the stream bed. Filtration developed under the dam due to thawing of [one word illegible]. The foundation of the dam, after removal of the topsoil and before being covered with clay, was left exposed for two summers. During that time the fractured [one or two words illegible] of the foundation thawed, the ice thawed and the cracks [one word illegible].

During preparation of the foundation of the dam the topsoil [one word illegible] in the section below and above the dam was removed with a large [one word illegible], and clay was filled in the body of the dam in strictly [one word illegible] quantities. In this connection fractured marlaceous sediments exposed after removal of the topsoil were left uncovered with clay in some places in the sections above and [one word illegible] the dam.

Dams No. 8 and 9. These dams are structurally analogous to the one just described. Dam No. 8, 10 m high and 80 m long at the crest, was completely built during the summer with bulldozers. The soil was processed in an open pit mine next to the dam and was transported to the construction site, leveled and rolled. The dam has been operating as a reservoir for 3 years.

The wooden spillway of the dam was constructed during winter. Because of the poor quality of construction operations considerable filtration was observed during the first year of operation at places where spillway constructions join the foundation, especially under the water apron. The first repairs were made during the first summer and filtration was completely arrested.

Dams No. 6 and 7 (Figure 7) are included in a complex of stream diversion and spring and rain flood control projects on a site located in the stream valley. The length of dam No. 6 at the crest is 285 m and height is 6.1 m. The corresponding figures for dam No. 7, located 2.3 km from the former, are 125 m and 8.1 m.

Both dams are structurally identical and are built of marlaceous soil with an antifiltration curtain made of wood panels. The body of the dam is mated with the foundation by an up to 2.2 m deep tooth with a trench in the less ice-saturated bedrock.

Here we have an example of how the plan of a dam was completely revised because of the conditions of the construction operations. The new plan made it possible to complete construction work and place the installation in operation on schedule at extremely low negative temperatures.

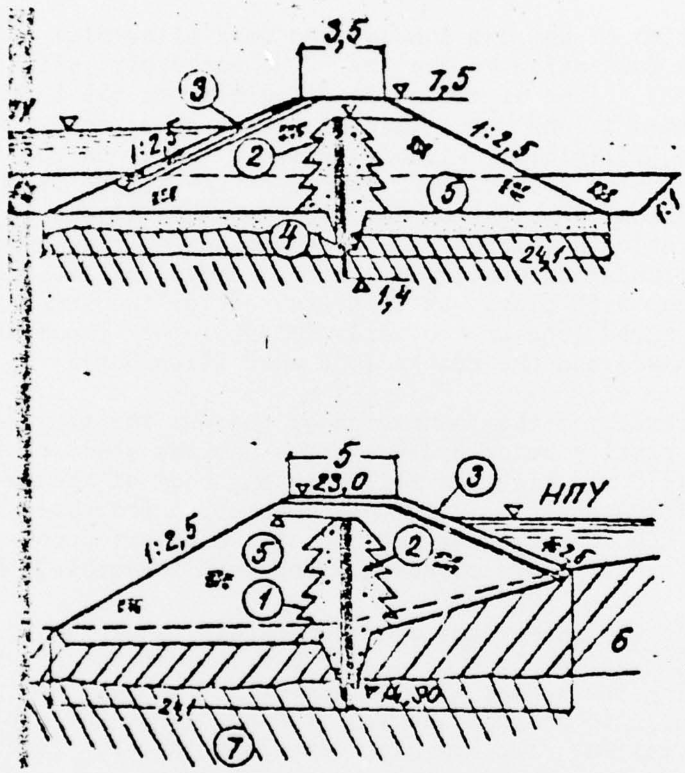

Figure 7. Dams No. 6 and 7: 1 -- wood panel diaphragm on [one word illegible] pilings; 2 -- sand-gravel core; 3 -- [one word illegible] with small rocks; 4 -- clay lock; 5 -- body of dam; 6 -- ice-saturated clay with rubble; 7 -- marlaceous rock.

In the foundation of the dam, the surface of which lies at a depth of 0.80 to 1.30 m, is deposited a topsoil layer, [one word illegible] gray silty loamy clay with plant fossils; [one word illegible] with a layer up to 1-1.2 m thick, ice-saturated greenish gray loamy clay with 20 to 65% river rock rubble. The apparent ice concentration ranges up to 25% of the total thickness of the stratum, it is [one word illegible] with crystals

and 1-5 m thick ice seams. Below that are deposited marl and marlaceous clay, which are less ice-saturated. During preparation of the foundation of the dam the top layer, peat and silty loamy clays were removed. The rubbly clays below them were completely cut through by the tooth of the dam. The latter was cut into marl.

The plans of the installation (plan b of the "Tsvetmetproyekt" Institute) are simple in the engineering sense and their construction would have posed no problem under different engineering-geological and climatic conditions.

Serious problems were encountered during completion of the operations. Indeed, the construction site was a swamp during the summer-fall seasons. The loamy soils that make up the stream valley floor are in the water-saturated state. The water yield of the soils is so [possibly high] that the seasonal thaw layer, up to 1-1.4 m thick, is a liquified mass. It is virtually impossible to operate trucks and excavators on such soils. It was virtually impossible to strip the topsoil, prepare the foundation for the dam and dig a trench for the tooth with bulldozers.

These operations could be completed only after the onset of freezing, when the liquified soils acquired adequate bearing strength. During that time the foundation was prepared and trenches were dug for the teeth of both dams. The marlaceous soils were loosened with bulldozers using BSN machines. It is important to note that loosening marlaceous soils by blasting was successful only after the seasonal thaw layer froze down to the permafrost. During the initial period of winter, before the complete freezing of the seasonal thaw layer, when a thaw zone still existed, the formation of camouflets was observed in the latter during blasting. Here, depending on the depth of freezing, the frozen crust either broke up into small chunks, or simply ruptured on the outside of the shot holes during the formation of large gas camouflets, expanding the mouth of the shot holes without breaking up the frozen crust.

The greatest difficulties were encountered during the construction and filling of the dam. The plan called for the filling of 10,700 m^3 of loamy clay in the upper dam and 2,850 m^3 in the lower, and 800 m^3 and [number illegible] m^3, respectively, in the teeth of the dams.

According to the plans the dams should have been filled with [one word illegible] loamy clay, but access to the construction site for preparing the foundations of the dams was possibly only after the onset of freezing. Meanwhile the complex of stream-diverting installations had to be constructed before the spring high waters in order to protect the mining complex from flooding, since mining operations at that time were already being conducted at substantially lower levels than the spring flood level. Therefore the entire volume of construction operations had to be completed during winter, before the onset of spring flooding, and the facilities had to be prepared to receive the spring flood waters.

The thawing of such great volumes of loamy clay and its filling into the body of a dam in the thawed condition at low ambient temperatures, reaching -50°C, posed a most difficult and laborious task.

It was necessary to find an engineering solution that would completely correspond to the requirements imposed.

Furthermore, the installations were supposed to be erected from local materials on short deadline at extremely low ambient temperatures.

We proposed, developed and built a design of dam filled with frozen loamy clays with a wooden antifiltration curtain. Both dams were filled with frozen marlaceous loamy clays from useful excavations.

The frozen loamy clay was filled into the dam in the form of chunks not larger than 25-80 cm. For this purpose the frozen chunks and pieces of soil excavated from the quarry were crushed directly on the construction site. The frozen loamy clay, delivered to the construction site, was first processed and then crushed by repeatedly running a DET-[several numbers or letters illegible] track-mounted tractor. After that the crushed loamy clay was moved by bulldozers from the crushing and preparation site into the body of the dam. There it was spread in 40 cm layers over the chart and compacted by repeatedly driving over it with MAZ-205 track-mounted dump trucks. Packed as such, the frozen loamy clay had a density of 1.23-1.35 t/m^3.

Loamy clay with up to 20-30% carbonate rock inclusion was packed into the dam. The natural [one word illegible] humidity of the soil varied from 22 to 28%.

The antifiltration curtain is a diaphragm of wood planks, installed on [one word illegible] pilings. For construction of the curtain holes were bored along the axis of the dam to the floor of the tooth trench with BU-20-2 cable-impact drilling rigs. These holes were drilled 2 m apart and light pole pilings were set in them. The [one word illegible] was made of two-layer board (40 and [numbers illegible] boards) panels with two layers of roofing felt between.

The panels were built ahead of time in the warm [one word illegible] and the diaphragm was assembled from the ready-made panels in two-three courses. The panels were butt-joined with a 15 cm overlap. For greater reliability in the butt joints the panels were covered with strips of felt. During installation of the panels the butt joints were also sealed with cement.

For reliable placement of the diaphragm in the foundation to prevent filtration at the interface between the diaphragm and the foundation, after the first course of panels was installed the [one word illegible] of the dam was packed with thawed loamy clay to a height of 0.50 m and was [one word illegible] compacted with hand rams. The frozen loamy clay was thawed

directly in situ with 4 × 3 m space heaters, constructed from the metal [one word illegible] that were being used. By this method it was possible to complete 10 diaphragm-foundation joints a day.

The body of the dam was expected to [one word illegible] as the frozen loamy clay melted. To reduce the harmful effect of such deformations of the bearing prisms of the dam on the [possibly diaphragm] and to prevent it from being damaged and destroyed, the core parts of the dam were filled with dry sand-[possibly gravel] mixture. The fill ensured reliable securing of the diaphragm panels during installation and also served the function of a back filter in the event of possible damage to the diaphragm. At the same time the sand-gravel mixture layer protected the panel diaphragm as a buffer between misalignment and mechanical damage during filling of the body of the dam with the frozen chunk [one word illegible]. The minimum thickness of the sand-gravel core was [number illegible].

During the spring-summer period of the first year of operation thawing of the frozen marlaceous loamy clays by [possibly self-compaction] resulted in up to 50 cm of subsidence. However, the dams were filled with a margin against the projected height by [illegible] cm. During the first year of operation, one day after [one word illegible] of the planned pressure head, filtration of water was observed in the left bank part of the upper slope, with a discharge rate of up to [illegible]. The presumed cause of filtration was misalignment of the diaphragm panel joints as a result of inadequate [one word illegible] filling and packing of the frozen chunk clay. Filling of the lower slope of the dam at the point of discharge of the filtration stream with local thawed soil stopped [one word illegible], and then filtration completely ceased. This dam has exhibited no filtration phenomena since then. During the first weeks of operation the pumping station operated with interruptions, the reservoir filled and the water level in it rose above the [one word illegible] of the top of the antifiltration diaphragm, but no undesirable consequences were observed. Both dams have been operating satisfactorily for [one or two words illegible].

Conclusions

1. During the construction and operation of frozen dams, just as for the construction of dams by the thaw method, but for their operation as such, frozen soils may be used for the foundation. However, the foundation soils must not be allowed to thaw. Filtration through the body and foundation of a dam should be completely precluded. Otherwise losses of the filtration resistance and overall strength of the facility will occur.

2. The requirement of ensuring against filtration through the body and foundation of a dam or in the bank [one word illegible] and its abutment with the spillway must also be observed during the construction of dams by the thaw method. Filtration eventually promotes the formation of a thaw zone, increased filtration [one word illegible] and the overall stability of a [possibly dam] on [possibly rocky] soil is lost.

3. During the construction of dams on ice-saturated sedimentary soils, the latter must be completely [possibly stripped] from the foundation if their thickness is insufficient, and [possibly replaced] with high-quality soils. If the thickness of ice-saturated soils is substantial, then the core of the dam must be [possibly filled] with less ice-saturated [possibly soils] as a tooth. The latter should completely cut through the [one word illegible] ice-saturated soils.

4. During the construction of low-pressure dams the prisms may be filled with marlaceous soils [one or two words illegible] its antifiltration system [one or two words illegible] wooden diaphragms.

5. The dimensions of the spillway [possibly gates] [possibly should be] determined on the basis of careful analysis of the [possibly hydrological] mode of the stream. [Possibly otherwise] the facilities [possibly may] experience accidents.

6. Wherever relief permits, the spillway should be built outside of the [one word illegible] front created by the dam. Otherwise filtration may occur, altering the thermal mode of the facilities, resulting in inevitable losses of filtration resistance.

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